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Effects of die surface patterning on lubrication in strip drawing

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ABSTRACT

Strip-drawing tests with annealed stainless steel samples involving small strains were used to investigate the effect of surface texturing in tribological applications involving mixed lubrication and plastic deformation. Dies were prepared with surface patterns composed of circular pockets and parallel grooves, and comparison tests were performed with highly polished dies. The effects of surface texturing were detected by friction force measurements and examination of the deformed strip surfaces, under conditions of oil lubrication. Surface patterns consisting of circular pockets with very low area coverage did not improve the tribological performance. For grooves with larger area coverage (≈25%), significant effects were observed on the friction between the dies and the strip, which were reflected in the drawing force. The performance was strongly influenced by the relative orientation between the grooves and the drawing direction. For grooves perpendicular to the drawing direction, the friction was greatly reduced; the grooves were believed to act as lubricant reservoirs and to induce microplastohydrodynamic lubrication. On the other hand, when the grooves were oriented parallel to the drawing direction, the friction was much greater and the strip surface finish became poorer; these grooves were believed to allow the lubricant to escape from the contact.

1. Introduction

In the strip-drawing process, plastic deformation of a metal strip takes place as it is pulled through a converging channel formed by stationary dies. The bar usually has a rectangular cross-section and the deformation condition approximates to plane strain. The deforming strip slides over the whole contact zone. Sliding generates frictional forces (F_1, F_2) that oppose the movement of the strip, as shown schematically in Fig. 1. The contribution of the friction force to the drawing force (D) is very important. Friction has an effect equivalent to the application of a back tension and thus lowers the interface pressure, but at the expense of a higher drawing force. Deformation in the strip occurs under the combination of the longitudinal (drawing) stress and the compressive stresses generated in the die. The purpose of strip drawing may be simply to improve dimensional tolerances, to improve surface finish, or to work-harden and thus increase the strength of the product. More frequently, though, it is carried out to achieve large cross-section reductions, which require more than one drawing pass (Le and Sutcliffe, 2002; Schey, 1983).

Under the very specific conditions of plastohydrodynamic (PHD) lubrication, it is possible to maintain a substantial fluid lubricant film between die and workpiece during drawing (Schey, 1983). In PHD, a viscous lubricant enters the deformation zone, forming a film due to the converging die geometry,

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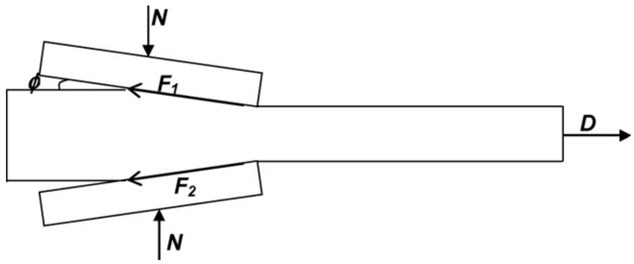

Fig. 1 – Forces acting during a strip-drawing test. *N* is the indentation force, *D* the drawing force, F_1 and F_2 are the friction forces between the strip and the two dies.

but this film is insufficient to maintain full die–workpiece separation. Differential yielding of the workpiece material results in local oil entrapment in surface pockets. As deformation proceeds, lubricant trapped in the pockets fails to keep up with surface extension, increasing the proportion of regions with boundary contact. Lubricant trapped in individual pockets behaves like a hydrostatic medium (Azushima et al., 1991; Bech et al., 1998). However, PHD is rare, and most metal-forming processes involve boundary or mixed lubrication (Kudo et al., 1982).

The existence of lubricant pockets has been confirmed by experiments in which surfaces deformed under mixed lubrication conditions are analysed (Bech et al., 1998). These suggest that the intentional formation of pockets in either the workpiece or the die surface might increase PHD lubrication, by mechanisms often referred to as microplastohydrodynamic (MPHD), with the size of the pockets being on a micrometre scale (Lo and Wilson, 1999).

The use of artificially formed lubricant pockets to improve lubrication in metal-forming processes (i.e. by the surface texturing of dies) has been experimentally investigated by several researchers (Azushima and Kudo, 1995; Bech et al., 1998; Ike, 1996; Sheu and Hector, 1999; Sheu et al., 1998; Sorensen et al., 1999; Steinhoff et al., 1996; Wihlborg, 2000) whose work has been mostly related to tests involving severe plastic deformation. In the present work, strip drawing was used as a model experiment to investigate the effects of controlled surface patterning on friction and lubrication in tribological situations which involve small extents of plastic deformation of the workpiece. In an associated study, the effect of surface texturing on the hydrodynamic lubrication of elastically loaded surfaces has also been examined (Costa and Hutchings, 2007). The drawing of thin metallic strips was used to ensure uniform deformation of the workpiece, since inhomogeneous deformation becomes significant when the mean thickness of the deforming body becomes much larger than the contact length (Schey, 1983). A viscous plain mineral oil was used as the lubricant, without any boundary lubricating additives, in order to enhance the influence of the lubricant film thickness on friction and drawing force.

2. Experimental methods

Experiments were performed with a laboratory-scale strip-drawing rig, in which the metal strip workpiece is attached to a shackle and drawn between a pair of stationary dies (Le and Sutcliffe, 2002). Special dies containing replaceable inserts were designed to allow various surface textures to be tested; the inserts were small, easy to handle and re-grind and/or re-polish, and texturing could be performed on the insert surfaces instead of on the whole die. Both the die bodies and the inserts were made from tool steel (BW1A) which was machined in the normalised state. They were then heat treated at 900 °C, oil-quenched and tempered at 200 °C for 2 h. The Vickers hardness of the die bodies and inserts after hardening and tempering was 650 ± 40 kgf mm^{-2}. The tolerance for parallelism along the length of the inserts was 10 μm, which helped to avoid inhomogeneous stress distributions during the tests. The inserts were mirror-polished with 1 μm diamond paste, and the insert surfaces were then patterned by photochemical texturing, as described elsewhere (Costa, 2005).

The taper angle (ϕ in Fig. 1) was estimated from the values of thickness reduction and contact length, measured directly on the workpieces. The values of thickness reduction were very small (between 1.3 and 2.2%), and contact lengths, dictated by indentation force and material flow stress, were around 5–10 mm, which gave effective die angles between 0.004 and 0.013 rad.

The surface topography of the textured inserts was measured with an optical interferometer (Zygo New Image 200). Sample nomenclature and geometric features for each pattern are summarised in Table 1. Patterns of grooves and circular pockets, as shown in Fig. 2, were tested, as well as a non-textured mirror-smooth surface as a control. In the tests to evaluate the effect of surface texture, one of the die inserts

Table 1 – Nomenclature and description of the geometric features of textured die inserts: *w*, width of the features; h_1, depth; *f*, fraction of area coverage

Insert	Shape	w (μm)	h_1 (μm)	f	h_1/w	Drawing direction
ST1	Circles	130 ± 10	3.6 ± 0.3	0.03	0.03	
ST2	Grooves	30 ± 5	3.0 ± 0.3	0.24	0.1	
ST3	Grooves	30 ± 5	3.0 ± 0.3	0.22	0.1